

# Ultrahigh Energy Neutrinos and the Highest Energy Cosmic Rays

G. Domokos and S. Kovács-Domokos  
Department of Physics and Astronomy  
The Johns Hopkins University  
Baltimore, MD 21218\*

Paul T. Mikulski  
Department of Physics  
United States Naval Academy  
Annapolis, MD 21402†

June 2000

## Abstract

It has been suggested that the characteristic energy of string models may be considerably lower than the observed Planck mass ( $\approx 10^{19}$  GeV). In such schemes, the unification of interactions takes place around the string scale, perhaps as low as a few tens of TeV. Consequently, at energies above the string scale, neutrinos acquire interactions comparable in strength to strong interactions. While they can propagate through the CMBR essentially uninhibited, in interactions with nuclei in the atmosphere they induce air showers comparable to proton induced ones. We conjecture that air showers above the Greisen-Zatsepin-Kuzmin (GZK) cutoff in the cosmic radiation are induced by such neutrinos. A Monte Carlo simulation shows that neutrino induced “anomalous” showers are virtually indistinguishable from proton induced ones on an event-by event basis. However, given sufficient

---

\*e-mail: skd@jhu.edu

†e-mail: mikulski@brass.mathsci.usna.edu

statistics in detectors (HiRes, OWL, Auger, ...), the post-GZK showers are expected to exhibit characteristics in the fluctuation pattern allowing a distinction between proton and neutrino induced showers.

Paper submitted to Neutrino2000, Sudbury June 2000

## 1 Introduction

The propagation of the highest energy cosmic rays (assumed to be protons) is limited predominantly by pion photoproduction on the photons of the cosmic microwave background (CMBR). This is the well known Greisen, Zatsepin, Kuzmin (GZK) effect, leading to a cutoff in the spectrum of primary cosmic rays at around  $6 \times 10^{19}$ eV in energy. No source of high energy protons can be much farther than about 20Mpc if the protons are to reach us without a substantial energy loss. A modern and careful calculation of the effect has been carried out by Hill and Schramm, ref. [1] which also contains references to the original papers. The physics of the GZK effect is very well known and it is not controversial: in fact, the energy in the CM system of the collision between a cosmic ray proton and a typical photon of the CMBR is just about sufficient to excite the  $\Delta$  resonance. Hence, one is dealing with low energy hadron physics explored for the past 45 years or so.

As a consequence, the observation of primary cosmic rays well above the GZK cutoff is a puzzle. For a sampling of the observations, one can consult a number of references, such as [2] (AGASA) , [3] (Fly's Eye) and Szabelski's review, [4]. In addition, the home page of the AGASA detector, [5] contains frequently updated information on the highest energy events observed. Apparently, there are no astronomical objects within 50 Mpc or so from the Milky Way capable of producing particles of the order of  $10^{20}$ eV, with the possible exception of M87, *cf* Biermann and Strittmatter, ref. [6].

It is to be noted that the highest energy event observed by Fly's Eye, see ref. [3] appears to have generated an extensive air shower (EAS) closely resembling one generated by a proton, as shown in ref. [7]. However, due to fluctuations in the development of an EAS, *one* event alone cannot uniquely determine the nature of the primary particle. A satisfactory resolution of this question requires a substantial amount of data collected by present and future detectors, such as HiRes, OWL, AIRWATCH, Auger *etc.*

Assuming the puzzle to be a real one, there are basically two types of explanations to be found in the literature.

- *Astrophysical ones*, with the work in ref. [8] being the most recent (and most credible) one. The authors of that reference assume that most (all?) of the post-GZK events are protons originating from M87. The observed near-isotropy of the distribution is explained by postulating a galactic wind.
- *Physics beyond the Standard Model or rare processes within the framework of the SM*. A fair sampling of those is contained in the proceedings of the University of Maryland *Workshop on Observing Giant Cosmic Ray Air Showers* [9].

In the light of recent, accelerator based experiments at LEP and the Tevatron, the only proposal based on the SM and its supersymmetric extensions which remains plausible is Weiler's [10]. In essence, Weiler proposes that UHE energy neutrinos interact with relic ones in our "cosmic neighborhood" and excite the  $Z$  resonance. The  $Z$ , in turn, decays predominantly into quark pairs. Hence, a proton can be created sufficiently close to us in order to evade the GZK cutoff.

Our proposal [11], following up on an earlier one [12], similarly conjectures that the post-GZK events are caused by neutrinos. Both Weiler and we agree that neutrinos penetrate the CMBR essentially uninhibited: the typical  $\sqrt{s}$  in an interaction between an UHE neutrino and a photon of the CMBR is of the order of 100MeV. This is in the realm of the SM and, in essence, the UHE neutrino does not interact with the CMBR.

In contrast to Weiler, however, we conjecture that the post-GZK events originate in the atmosphere, due to new physics. This may have some advantages as far as the energetics at the source of neutrinos is concerned. Moreover, as soon as a sufficient number of post-GZK events will be collected, the hypothesis will become relatively easily testable.

The approximate isotropy of the post-GZK events receives the same explanation in Weiler's scenario as in ours: neutrinos do not interact with the CMBR and UHE neutrinos generated by a multitude of sources reach us uninhibited.

In the following section we briefly outline the argument leading to a *precocious unification and some of its consequences*, based on ref. [11]. New

results are presented in the section describing the MC simulation of post-GZK showers. The last section contains a discussion of the results.

## 2 Precocious Unification

“Old fashioned” grand unification theories (GUT) as well as string models were based on the notion that the unification of forces (including gravity) can take place only around the Planck energy. Recent work by Lykken [13], Dimopoulos *et al.* [14], Dienes *et al.* [15]<sup>1</sup> questions this dogma, by pointing out that the existence of extra (probably compactified) dimensions in various string models allows one to separate the string scale from the observed Planck scale ( $M_P \simeq 10^{19} \text{ GeV}$ ). In fact, the string scale can be as low as a few or a few tens of a TeV, without violating known experimental constraints, including the lifetime of the proton.

It has to be emphasized that such a scenario lacks, at this time, a solid dynamical underpinning. Nevertheless, it is very interesting from the experimental/observational point of view, and, most importantly, its main consequences can be tested within the next decade.

As it was pointed out in ref. [11], low mass scale *string*-based unification implies a rapidly (*exponentially*) rising level density of intermediate excited states involved in any given reaction at energies either soon to be available for experimentation (LHC) or at modern cosmic ray detectors<sup>2</sup>. As a consequence, cross sections of essentially *all* relevant reactions reach their value dictated by the unified theory very rapidly. This is a pleasing and almost model independent consequence of such scenarios: all string models give rise to an exponentially rising level density of excited states<sup>3</sup>. (The transition from a logarithmical to a power behavior of the running couplings has been particularly stressed by Dienes *et al.* [15]). In ref. [11], we could merely test the plausibility of the scenario outlined above. It was found that with the string entropy growing as  $S \simeq \sqrt{N}$  and with reasonable structure functions, a cross section of the order of the strong one can be reached at laboratory

---

<sup>1</sup>Due to the rapidly increasing number of works on this subject, here we can only cite the *earliest* articles of these authors on the topic.

<sup>2</sup>One recalls that if a particle – of almost any species – at a laboratory energy of the order of  $10^{20} \text{ eV}$  interacts with a nucleus in the atmosphere, the CMS energy of the reaction is of the order of a few hundred TeV.

<sup>3</sup>We thank K. Dienes for a correspondence on this topic.

energies ranging between  $10^{19}$  and  $10^{20}$  eV. The characteristic energy (inverse Regge slope) required for this is of the order of a few TeV. (Here  $N$  stands for the index of the level of excitation.) In any string model, a string entropy given above translates into a level density rising as

$$\rho \simeq \exp(s/s_0)^{1/2},$$

where  $s_0$  is the inverse Regge slope. In most models there is a power behaved prefactor in the expression of the level density. We found, however that the results are insensitive to the prefactor and it was omitted.

### 3 Characteristics of the “anomalous” showers.

For the sake of simplicity, neutrino induced showers in the energy region around and above the characteristic energy are henceforth called “anomalous”.

We assumed the following characteristics of the elementary processes giving rise to anomalous showers.

- Around the CMS energy  $\simeq \sqrt{s_0}$ , the neutrino – quark cross section begins to rise above its Standard Model value as dictated by the level density of  $s$ -channel excitations given above. The exponential rise continues until the cross section reaches a prescribed fraction (say,  $1/2$ ) of the strong cross section. Thereafter, the cross section levels off: unitarity does not allow cross sections which rise exponentially forever.
- As long as  $s$  remains larger than about  $s_0$ , any interaction produces quarks and leptons in roughly equal numbers. Once  $s$  drops below  $s_0$ , the particles interact with cross sections as given by the Standard Model. Quark production in lepton induced reactions and lepton production in quark (*i.e.* hadron) induced reactions was neglected in the latter energy range.

By experimenting with a variety of functions describing the rise and leveling off of the cross sections, we found that the final results were insensitive to the

precise form of the function. For that reason, most of the shower simulations were carried out using a step function<sup>4</sup>.

The development of the “anomalous” showers was modeled by means of a one dimensional MC. Standard model processes were modeled along fairly standard lines. One of the main innovations in the program was that input data could be modeled in a flexible way, so that it was relatively easy to experiment with various assumptions. The model is described in detail in ref. [17].

Here we present data assuming that at unification the cross section is approximately 1/2 of a SM hadronic cross section, extrapolated to the characteristic energy ( $s_0$ ) by means of a quadratic polynomial in  $\ln s$ . In the following Figure we display the average longitudinal profile of “anomalous” showers. For comparison, we also plot the average longitudinal profile of a proton induced shower. The profile of the proton induced shower is in reasonably good agreement with other calculations. (It has to be noted that there exist considerable uncertainties in a MC simulation of showers, largely due to the lack of direct measurements of cross sections, multiplicities, *etc.* in the relevant energy region. For a detailed discussion, *cf.* [17].)

---

<sup>4</sup>It was pointed out by Burdman *et al.* [16] that, strictly speaking, any step function threshold violates unitarity. This occurs because if the imaginary part of an amplitude has a step function discontinuity, its real part is (logarithmically) infinite at the point of discontinuity. However, as long as we deal with cross sections only, approximating a rapid rise by a step function does no harm.

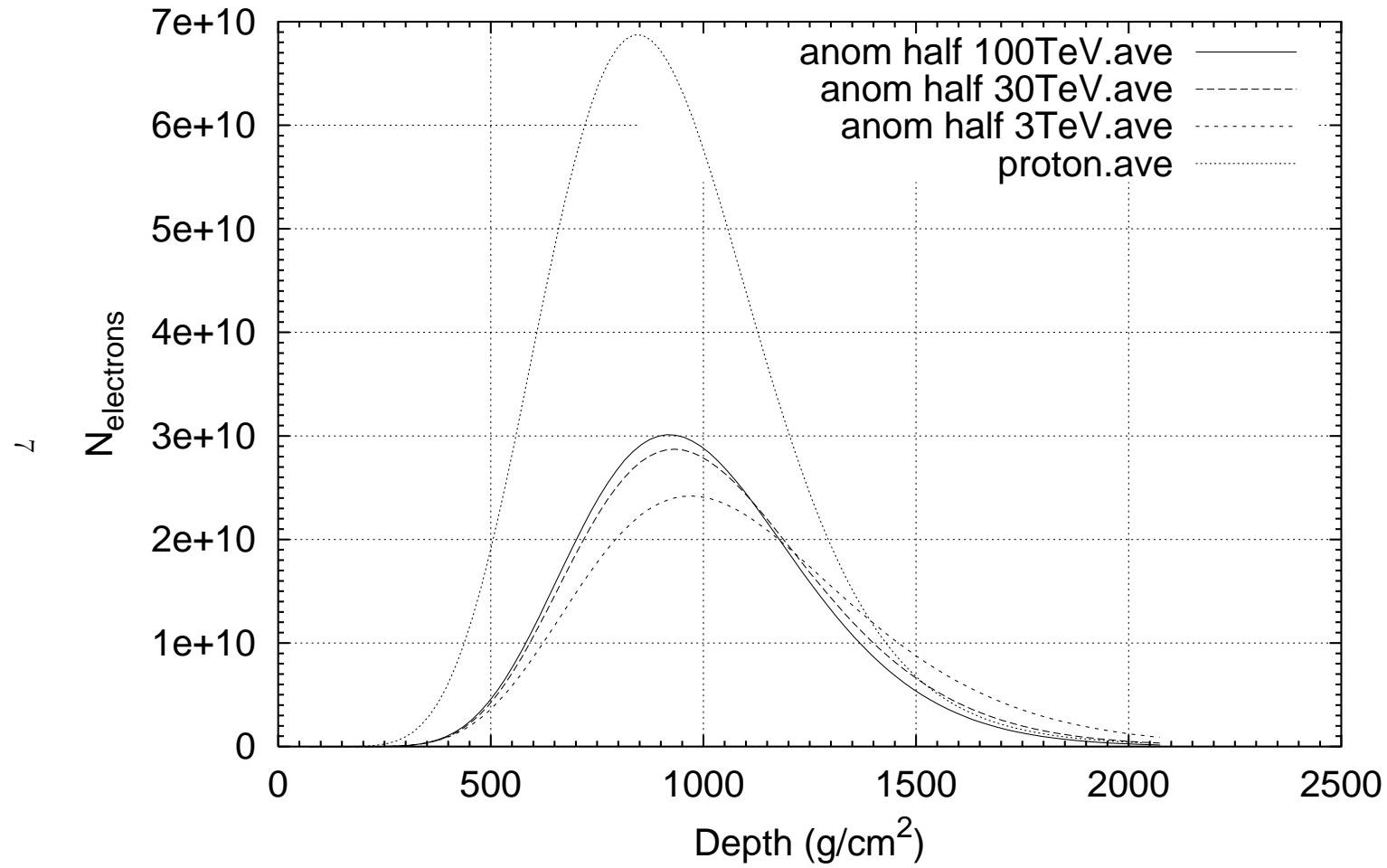


Fig. 1. Average anomalous shower profile

The development of the “anomalous” showers has been simulated for three values of  $s_0$ , as shown in Fig. 1. One sees a few prominent features in this Figure.

- The multiplicity of electrons around  $\langle X_{max} \rangle$  is about half of that contained in a proton induced shower. This is due to the fact that, if forces are unified, a substantial part of the primary energy goes into prompt lepton production; lepton interaction cross sections and multiplicities are lower than hadronic ones. Consistent with this picture is the result that the electron deficiency *increases* with *decreasing*  $s_0$ . For a lower characteristic energy, the prompt lepton production due to unification takes place for a longer portion of the shower after the first interaction.
- For the same reason as stated above, the position of  $\langle X_{max} \rangle$  is somewhat deeper than in a proton induced shower. However, the value of  $\langle X_{max} \rangle$  is, apparently, a rather slowly varying function of  $s_0$ .

It is not very likely that such features can be distinguished on an *event-by event* basis. For instance, if the electron number is smaller, one is likely to interpret the event as having a smaller primary energy. Likewise, an  $X_{max}$  larger than the expected one (of the order of  $850\text{g/cm}^2$ ) is likely to be interpreted as a fluctuation in the shower development.

There is, however, a *substantial* difference in the fluctuations around the shower maximum. In view of the fact that in the near future one is likely to have only a limited number of post-GZK events, we decided to characterize the fluctuations by a single parameter, namely the rms deviation from the mean value of  $X_{max}$ . In Figure 2, we plotted the rms deviations for the same values of  $s_0$  as in Fig. 1 and again, for comparison, the rms fluctuation for proton induced showers.

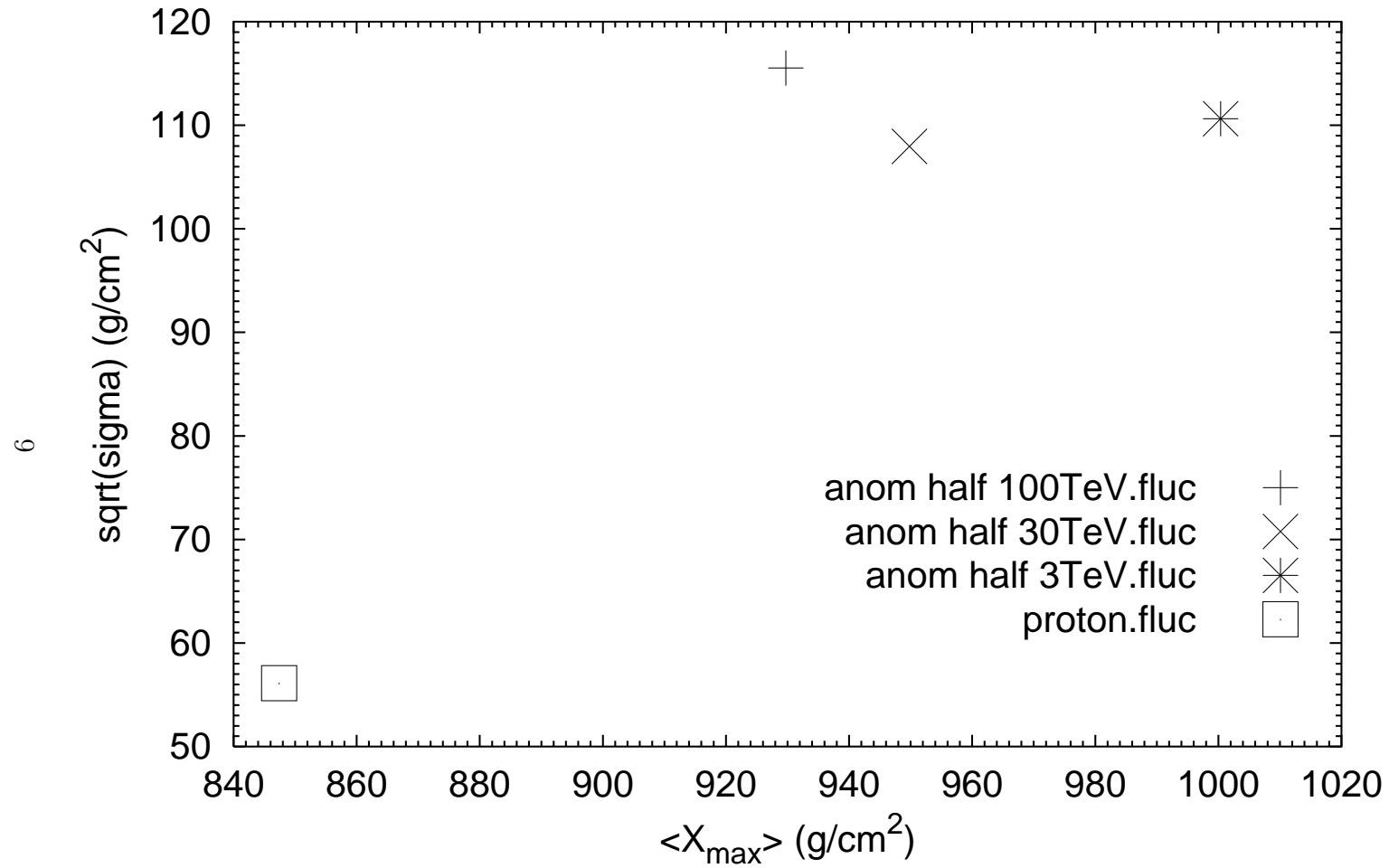


Fig. 2. RMS fluctuation of  $X_{\max}$

There are two main features discernible in Fig. 2.

- The rms fluctuation around  $\langle X_{max} \rangle$  increases from about  $55\text{g/cm}^2$  (proton induced showers) to a fluctuation about a factor of 2 or so larger in the case of “anomalous” showers.
- As in Fig. 1, the dependence on  $s_0$  is weak. In this MC simulation, we suspect that the differences between rms fluctuations for various values of  $s_0$  are largely due to statistical fluctuations in the simulation itself: there appears to be no systematic trend in the correlation between  $\langle X_{max} \rangle$  and the rms fluctuation.

It is easy to understand the main features displayed in Fig. 2 in terms of the “new physics” involved. It is well known that in the development of a cascade, if the latter is dominated by processes of small cross section and/or small multiplicities, the cascade exhibits large fluctuations. The “new physics” as conjectured here, contributes in this way to the initial stages of the cascade; hence, a somewhat dramatic increase of the fluctuations comes as no surprise.

## 4 Discussion

Even though there is no reliable dynamical theory describing low scale string physics yet, the basic aspects of the scenario exploited here are very attractive. (Among other things, the hierarchy problem of interactions and masses of elementary particles is likely to be alleviated. It was also pointed out by Dienes *et al.* [15] some time ago that a low scale unification does not have to lead to a rapid proton decay as it was previously believed.)

The study of the highest energy cosmic rays probably provides an interesting laboratory for the study of these ideas, complementing lower energy, accelerator based experiments.

Some comments are in order regarding the results presented here and on open questions. As emphasized in the preceding Section, all our results depend rather weakly on the magnitude of the characteristic energy. Preliminary calculations also indicate that variations of the cross section at unification does not affect the qualitative aspects of the results very much. For instance, if we assume that the cross section at unification equals the extrapolated value of the hadronic cross section,  $\langle X_{max} \rangle$  gets somewhat closer to

its value in proton induced showers. Likewise, the rms fluctuation around  $X_{max}$  becomes somewhat smaller. However, the shower is not identical to a proton induced one. This is due to the fact that in the first few interactions, roughly half of the energy ends up in leptons; when the energy drops below its critical value, the latter contribute to the evolution of the shower through low multiplicity interactions.

One of the important open questions is about the astrophysical origin of UHE neutrinos. It appears that the production of particles of any kind of energies around  $10^{19}\text{eV}$  and above is an unsolved and challenging problem in astrophysics. If one wants to remain within the framework of the SM, the production of neutrinos of similar energies can take place as a result of the weak decays of pions and other hadrons. In order to excite the  $Z$  resonance on relic neutrinos, the incident neutrino energy has to be of the order of  $10^{24}\text{eV}$ . Using a straightforward extrapolation of known hadronic cross sections and multiplicities, one concludes that protons of even higher energies are needed. This may seriously aggravate the astrophysical problem.

If, however, the incident neutrino initiates a shower on an “air nucleus”<sup>5</sup>, it only needs an energy approximately equal to that of an incident proton. It is not clear at present whether the “new physics” can contribute to the solution of the astrophysical problem.

## References

- [1] C.T. Hill and D.N. Shramm, Phys. Rev. **D 31**, 564 (1985).
- [2] M. Takeda *et al.*, Phys. Rev. Lett. **81**, 1163 (1988); S. Yoshida *et al.*, Astropart. Phys. **3**, 105 (1995); N. Hayashida *et al.*, Phys. Rev. Lett. **73**, 3491 (1994).
- [3] D.J. Bird *et al.*, Phys. Rev. Lett. **71**, 3401 (1993); Astrophys. J. **424**, 491 (1994); *ibid.* **441**, 144 (1995)
- [4] J. Szabelski, e-print astro-ph/9710191.
- [5] <http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/results.html>

---

<sup>5</sup>An “air nucleus” is the average of  $O$  and  $N$  nuclei, weighted with the concentration of each in the atmosphere.

- [6] P.L. Biermann and P. Strittmatter, Ap. J. **322**, 643 (1987). See also B. Wiebel-Sooth and P.L. Biermann, in Landoldt-Börnstein, vol. VI/3c. Springer Verlag (1999).
- [7] F. Halzen, R.A. Vazquez, T. Stanev and H.P. Vankov, Astropart. Phys. **3**, 151 (1995).
- [8] E.-J. Ahn, G. Medina-Tanco, P.L. Biermann, and T. Stanev, e-print astro-ph/9911123 (1999).
- [9] *Workshop on Observing Giant Cosmic Ray Air Showers from  $> 10^{20} \text{ eV}$  Particles from Space*, edited by J.F. Krizmanic, J.F. Ormes and R.E. Streitmatter, AIP Conf. Proc. No. 433. (AIP, New York, 1998.)
- [10] T.J. Weiler, e-print hep-ph/9710431; Astropart. Phys. **11**, 303 (1999).
- [11] G. Domokos and S. Kovács-Domokos, Phys. Rev. Letters **82**, 1366 (1999).
- [12] G. Domokos and S. Nussinov, Phys. Letters **B 187**, 372 (1987); G. Domokos and S. Kovács-Domokos, Phys. Rev. **D 38**, 2833 (1988).
- [13] J.D. Lykken, Phys. Rev. **D 54**, 3693 (1996).
- [14] I. Antoniadis, S. Dimopoulos and G. Dvali, Nucl. Phys. **B 516**, 70 (1997).
- [15] K. Dienes, E. Dudas and T. Gheretta, Phys. Letters **B 436**, 55 (1998).
- [16] G. Burdman, F. Halzen and R. Gandhi, Phys. Letters **B417**, 107 (1998).
- [17] Paul. T. Mikulski, “Extensive Air Showers: Model Dependence and the Longitudinal Profile”. Dissertation, Johns Hopkins University, Baltimore, MD.